Zero-carbon Ammonia-Powered Turboelectric Propulsion System (ZAPturbo)

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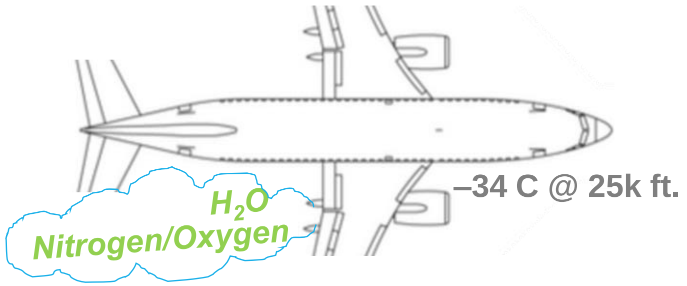
Raytheon Technologies Research Center (RTRC)

Project Vision

- Provide a *liquid-fueled, carbon-free, non-cryogenic* aircraft propulsion system for future flight.
- Leverage the unique properties of ammonia to achieve ultra-high energy efficiency (66%), to help *offset the extra weight-per-energy of ammonia*.

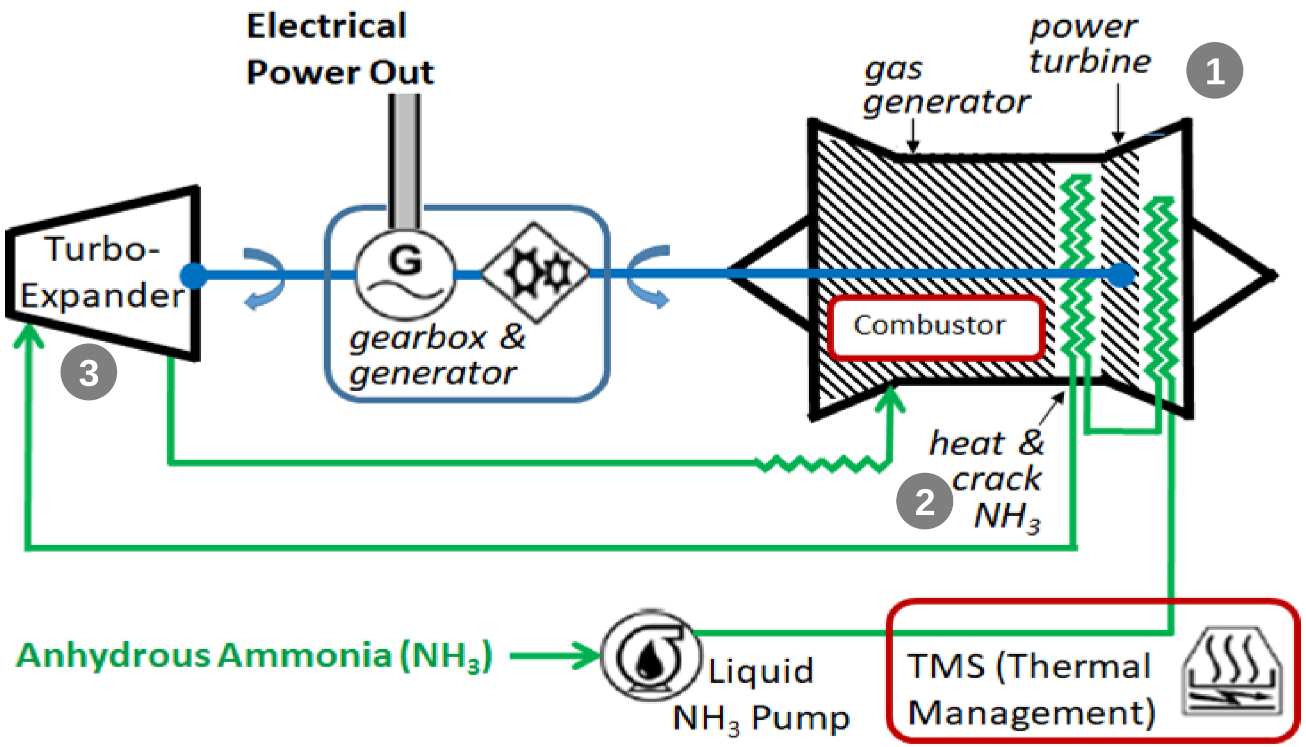


REEACH / ASCEND / CABLES
Annual Program Review Meeting
June 28-30, 2022

This presentation contains no technical data subject to the ITAR or EAR.

ZAPturbo Phase-1 overview: Technical Approach (3 tasks + T2M)

- Use NH_3 thermal properties for significant heat recapture to obtain <u>high efficiency</u>:
  - ➢ Offset weight of NH_3 fuel
- NH_3 cracking with<u>out</u> separation
  $2\ NH_3 \rightarrow 3\ H_2 + N_2$
- Eco-friendly:
  - ✓ ***Zero-carbon; -and-***
  - ✓ ***Zero-nvPM (no soot!)***
- "Open-loop" combined cycle
  (or ***regenerative cooling cycle***)
  (or ***chemical recuperation***)
- Maximum benefit obtained with:
  - ➢ High-pressure catalytic cracker
  - ➢ Ammonia turboexpander



1
Year-1 focus
2
3
Phase-1 technical effort (System & Risk Reduction)

4 ***Tech-to-Market (T2M)***

ZAPturbo – Team

Team member	Location	Role in project
Raytheon Technologies Research Center (RTRC)	East Hartford, CT	Project lead (prime) for overall system. Experimental tasks for ammonia cracking and turboexpander components.
Pratt & Whitney	East Hartford, CT	System modeling & analysis: aircraft mission analysis; gas turbine performance & integration, flowpath, & weight/cost estimates.
Gas Technology Institute	Des Plaines, IL	Ammonia handling & safety, storage, economics, TT&O / T2M.

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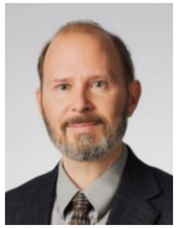

Lance Smith (PI)
Combustion & Fuels


Sean Emerson
Catalysis & Chem Eng. Team Lead


Brian Holley
Aerodynamics & Turbine Performance


Ulf Jonsson
Rotating & Fluid / NH_3 Machinery


Bob Dold
Mechanical Design & Analysis

Brent Staubach – Advanced Concepts & Technology Group Leader: Oversight of PW system modeling, cycle analysis, & integration

Jill Klinowski – Technical Coordinator for Technology Programs: Flight mission & engine-system analysis; engine integration studies

gti


Howard Meyer
Gas Processing & Separations, NH_3 Infrastructure, ARPAe/T2M experience


Ronald Stanis
Gas Conversion Tech., TT&O, Ammonia Energy Assoc. Representative


Travis Pyrzynski
NH_3 Experience & Process Safety Management, Lab Procedures & Protocols

ZAPturbo – Optimizing Efficiency with NH_3 & Electric Powertrain

Hybrid-Electric Architecture for High Efficiency

- Cruise-optimized:
  - NH_3 cracking unit: size/weight optimized for cruise power & flows
  - Gas turbine: high-OPR, high-TRIT operation for efficiency @ cruise
  - Gas turbine thrust lapse enables climb power capability: same "reduced" conditions at cruise & climb
- Battery-boost for takeoff power only (recharged during cruise)
- Efficient AC-AC powertrain at turboelectric cruise

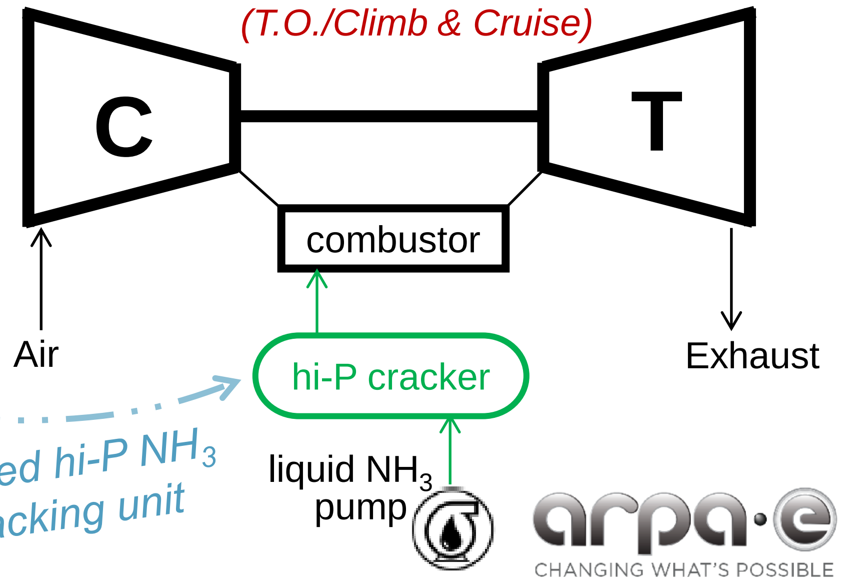
	Takeoff	Climbout	Climb	Hold	Cruise	Descend
Time (hours)	0.0833	0.1667	0.25	0.333	5.00	0.50
ESPG Power (% of 26-MW peak)	100%	70%	50%	35%	35%	30%
Power from fuel (% of peak)	70%	70%	50%	35%	35.50%	30%
Power from battery (% of peak)	30%	0%	0%	0%	-0.50%	0%

system-analysis cases (T.O./Climb & Cruise)

Use Ammonia's Thermal Absorption Capacity for High Efficiency

- NH_3 thermal absorption capacity, for waste-heat recovery:
  - High heat of vaporization & high heat capacity
  - No NH_3 temperature limit – coke-free heating
  - Endothermic cracking (coke-free)
- $2\,NH_3 \rightarrow N_2 + 3\,H_2$ …… $\Delta H = 2.7$ MJ/kg-NH_3 (15% gain)
- Hot fuel & NH_3 products provide further gains (5 – 10%)

Need hi-P NH_3 cracking unit



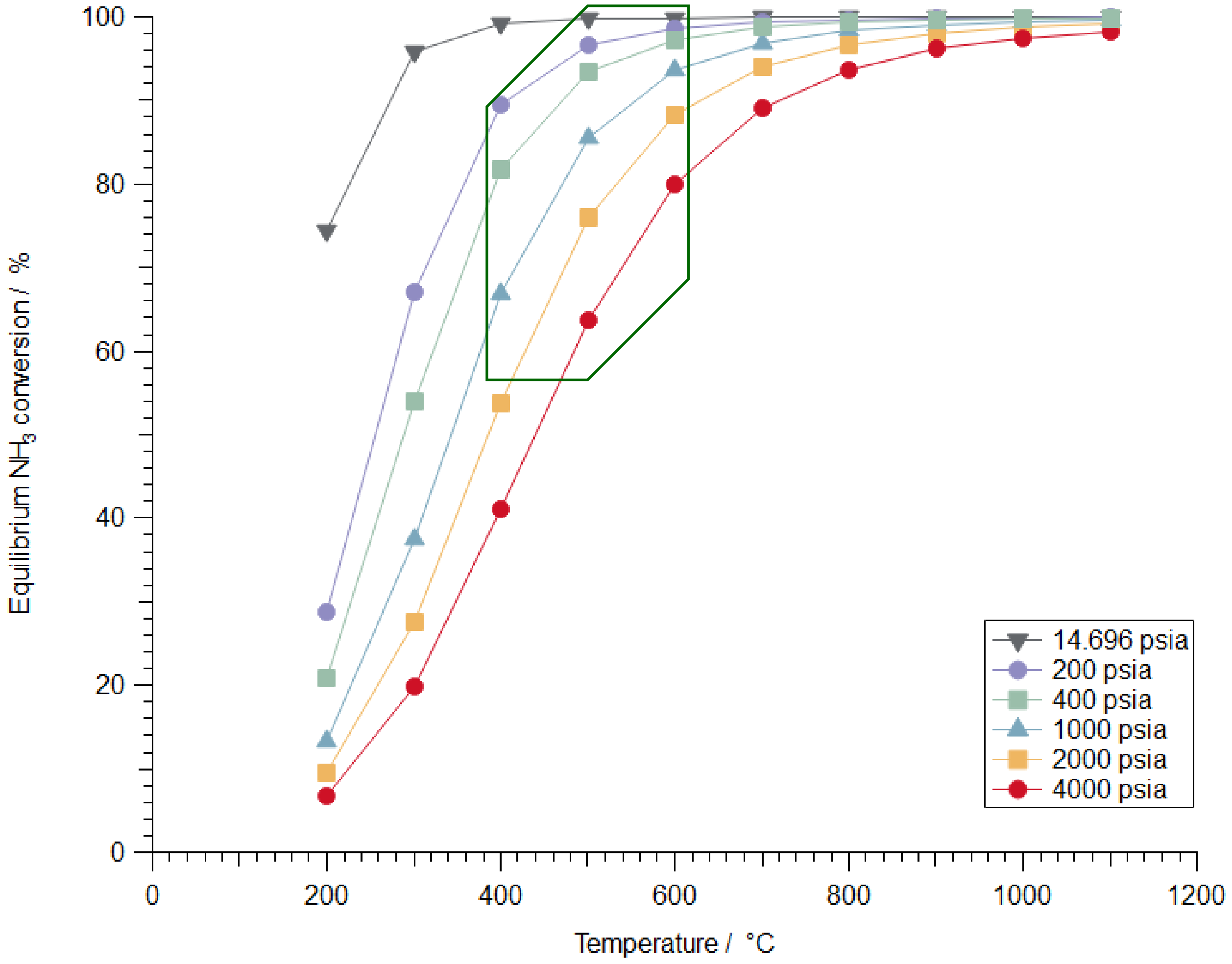
Challenge: Ammonia Decomposition/Cracking Chemistry

Ammonia Decomposition/Cracking

- $NH_3 + \Delta H \rightleftharpoons \frac{1}{2}N_2 + \frac{3}{2}H_2$
- Endothermic reaction (requires heat input)
- Ammonia synthesis favored at high pressure
- Decomposition favored at low pressure
  - >99.9% conversion at 1 atm, 400-800 °C
- High pressure needed as aircraft gas turbine fuel
- *Literature sparse/absent for high-P cracking data*

– Supercritical conditions
- NH_3: T_C = 132.35 °C; P_c = 112.8 bar (1636 psia)
- N_2: T_C = -146.94 °C; P_c = 33.9 bar (492 psia)
- H_2: T_C = -240.21 °C; P_c = 12.86 bar (188 psia)

Chemical Equilibrium



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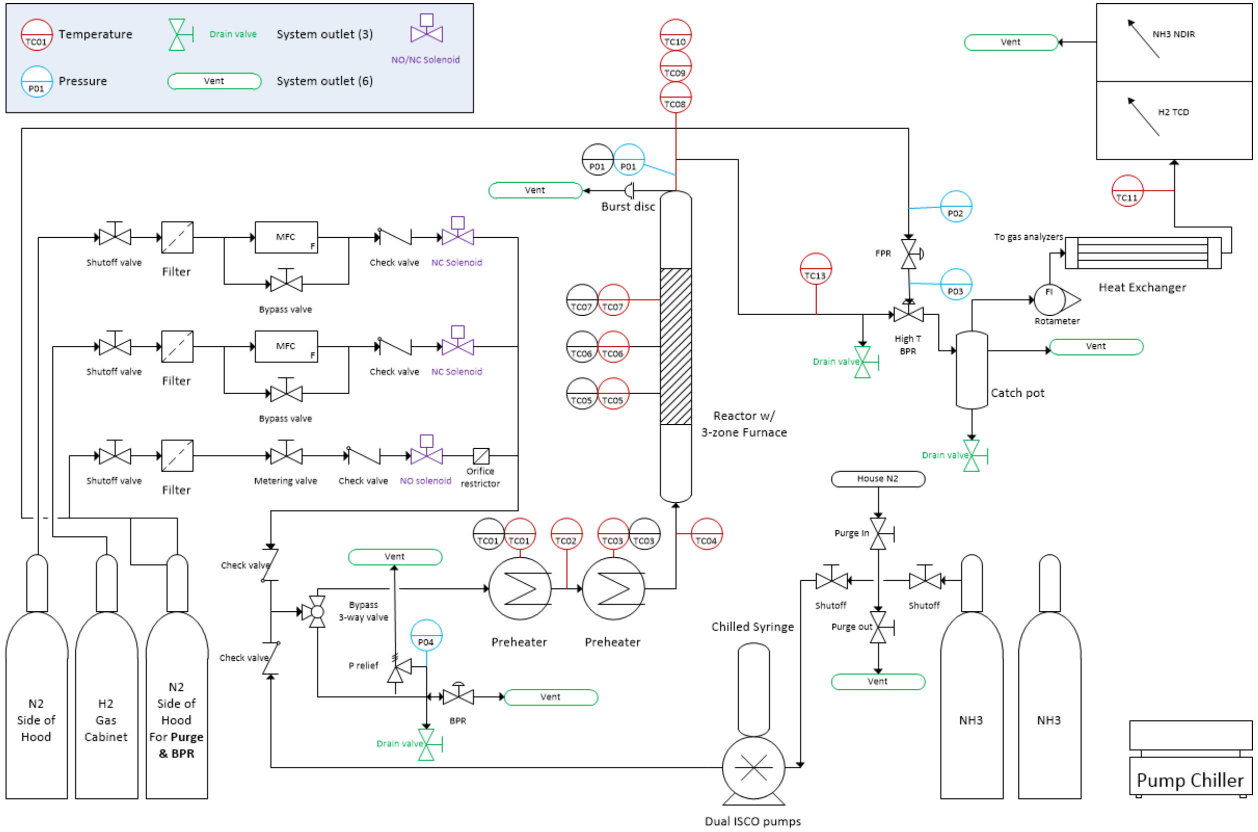
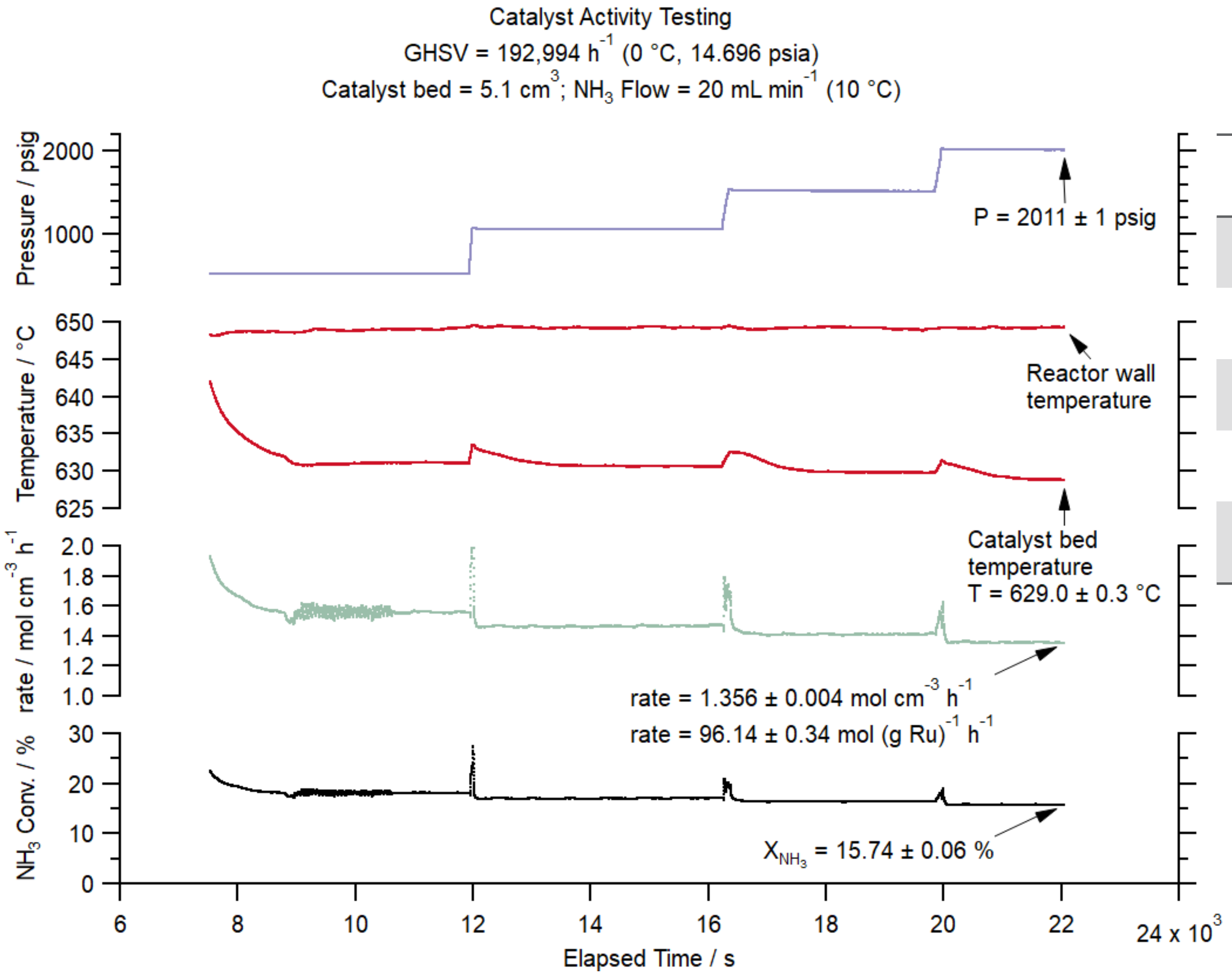
Ammonia Cracking Rig Built & Commissioned in Year-1



- Major rig components received from vendor Nov. 2021
- Assembly, modifications, & installation into test facility Mar. 2022
- First **<u>cracking catalyst test results obtained Apr. 2022</u>**

Initial Catalyst Testing: <u>Kinetics</u> vs Pressure (630 ± 2 °C)

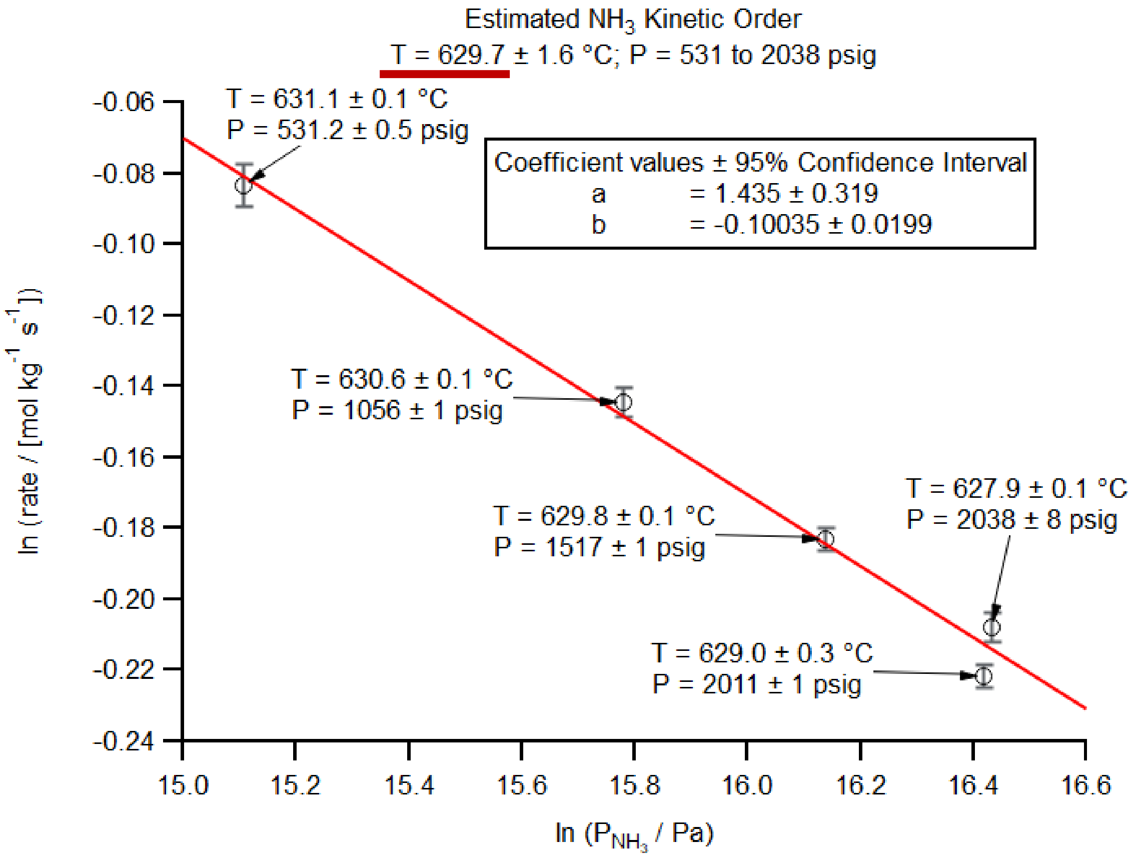


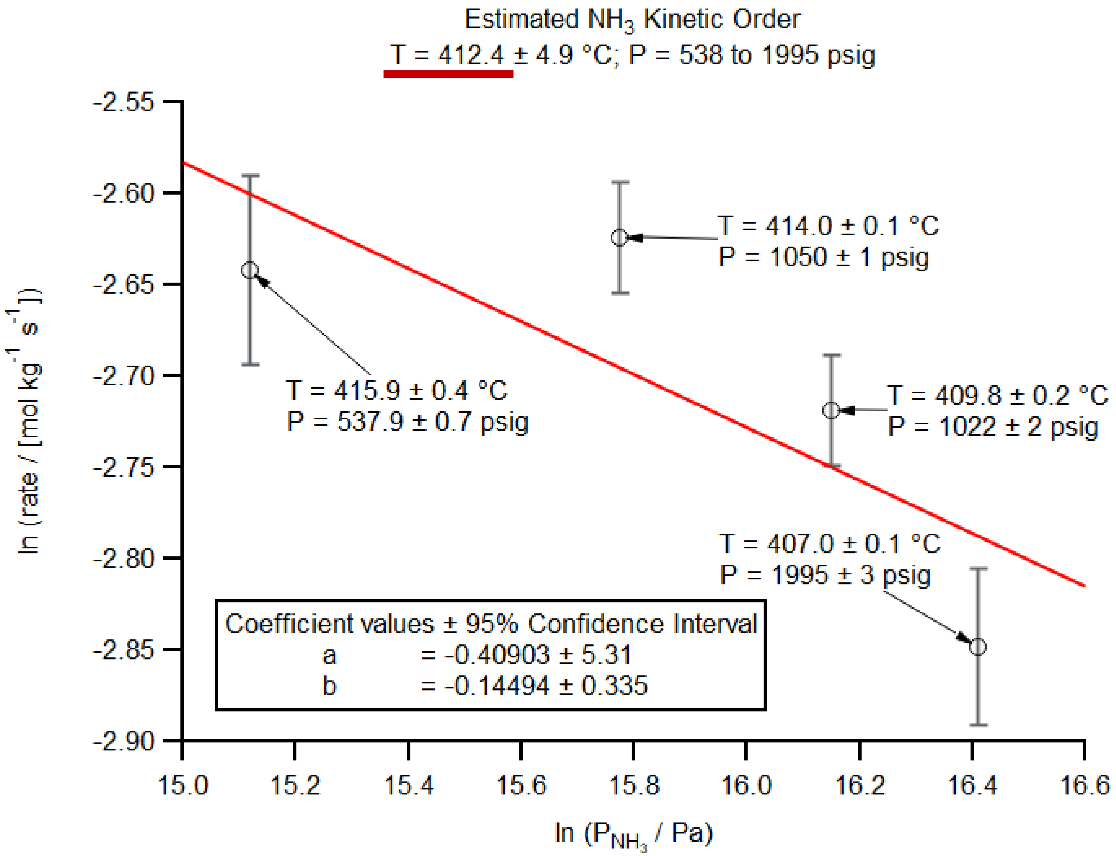
P / psig	T / °C	NH_3 Conversion / %	NH_3 rate / mol NH_3 cm^{-3} h^{-1}	NH_3 rate / mol NH_3 (g Ru)$^{-1}$ h^{-1}
531.2 ± 0.5	631.1 ± 0.1	18.01± 0.11	1.557 ± 0.010	110.4 ± 0.7
1056 ± 1	630.6 ± 0.1	17.01 ± 0.06	1.465 ± 0.005	103.9 ± 0.4
1517 ± 1	629.8 ± 0.1	16.36 ± 0.05	1.409 ± 0.004	99.91 ± 0.32
2011 ± 1	629.0 ± 0.3	15.74 ± 0.06	1.356 ± 0.004	96.14 ± 0.34
2038 ± 8 (Initial test)	627.9 ± 0.1	15.96 ± 0.07	1.374 ± 0.006	97.47 ± 0.40

√

- Incremented pressure at constant temperature
- <u>Small reactor bed (5.1 cm^3)</u> with high NH_3 flow
- Conversion <20% for estimating differential rates
- Observed slight decrease in activity as pressure increased ……… $\propto \sim P^{-0.1}$

Preliminary Pressure Effect on Cracking (500 – 2000 psia)





- Decomposition rate total/ammonia pressure dependence ∝ $P^{-0.10\pm0.02}$ at 630 ± 2 °C
- Pressure dependence ∝ $P^{-0.14\pm0.34}$ at 412 ± 5 °C
- Preliminary data consistent with expected overall pressure dependence of ≈ $P^{-0.27}$ from Temkin kinetics

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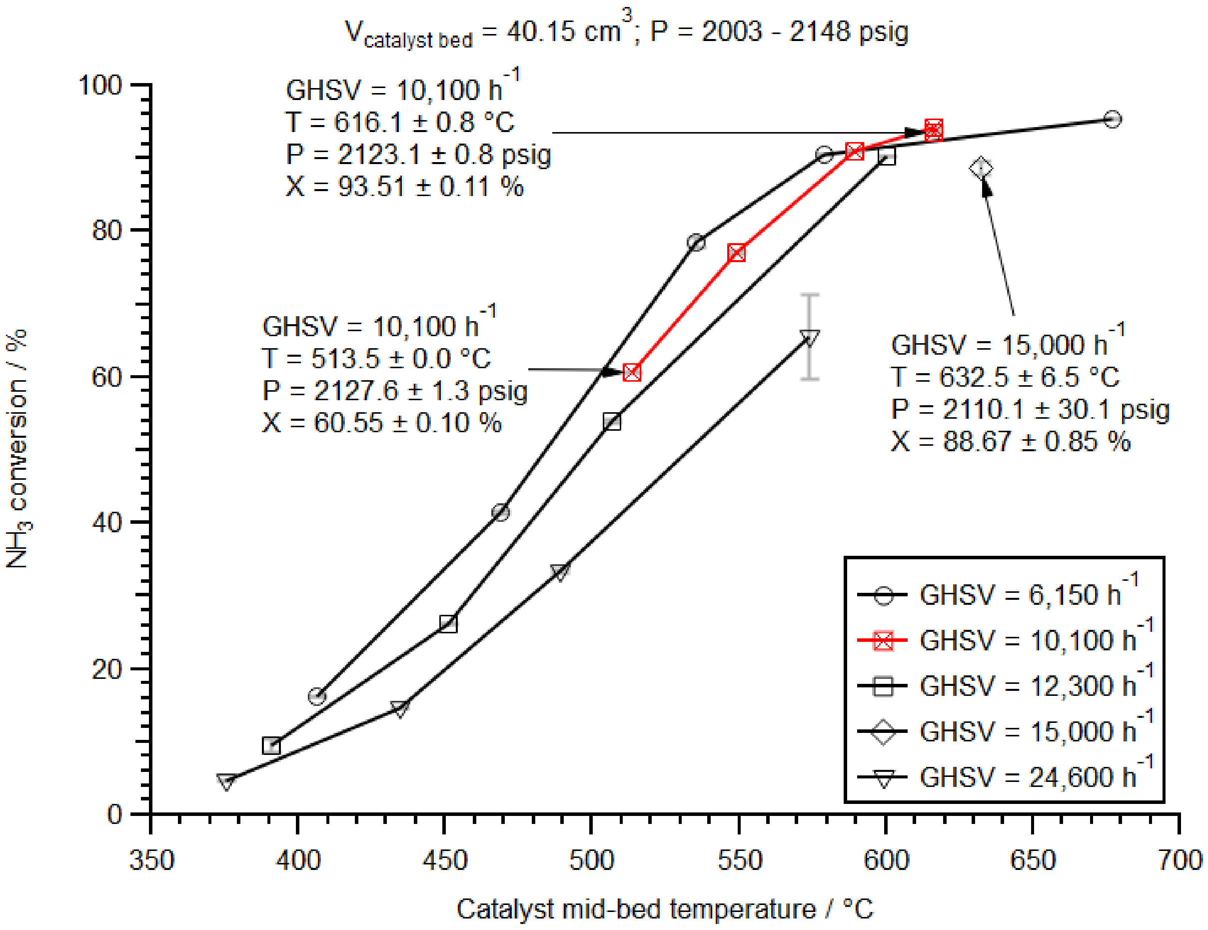
Catalytic Reactor Testing: Activity Tests at ≥2000 psia



Catalyst Activity Achieved for GHSV ≥ 10,000 h^{-1}

- Targeting 100 L reactor for single-aisle (S.A.) aircraft
- Reactor bed is 40 cm^3 (1/2500 S.A. scale) for testing
- Can achieve ≥60 % at ≥514 °C
- Conversion ≥90 % at ≥616 °C

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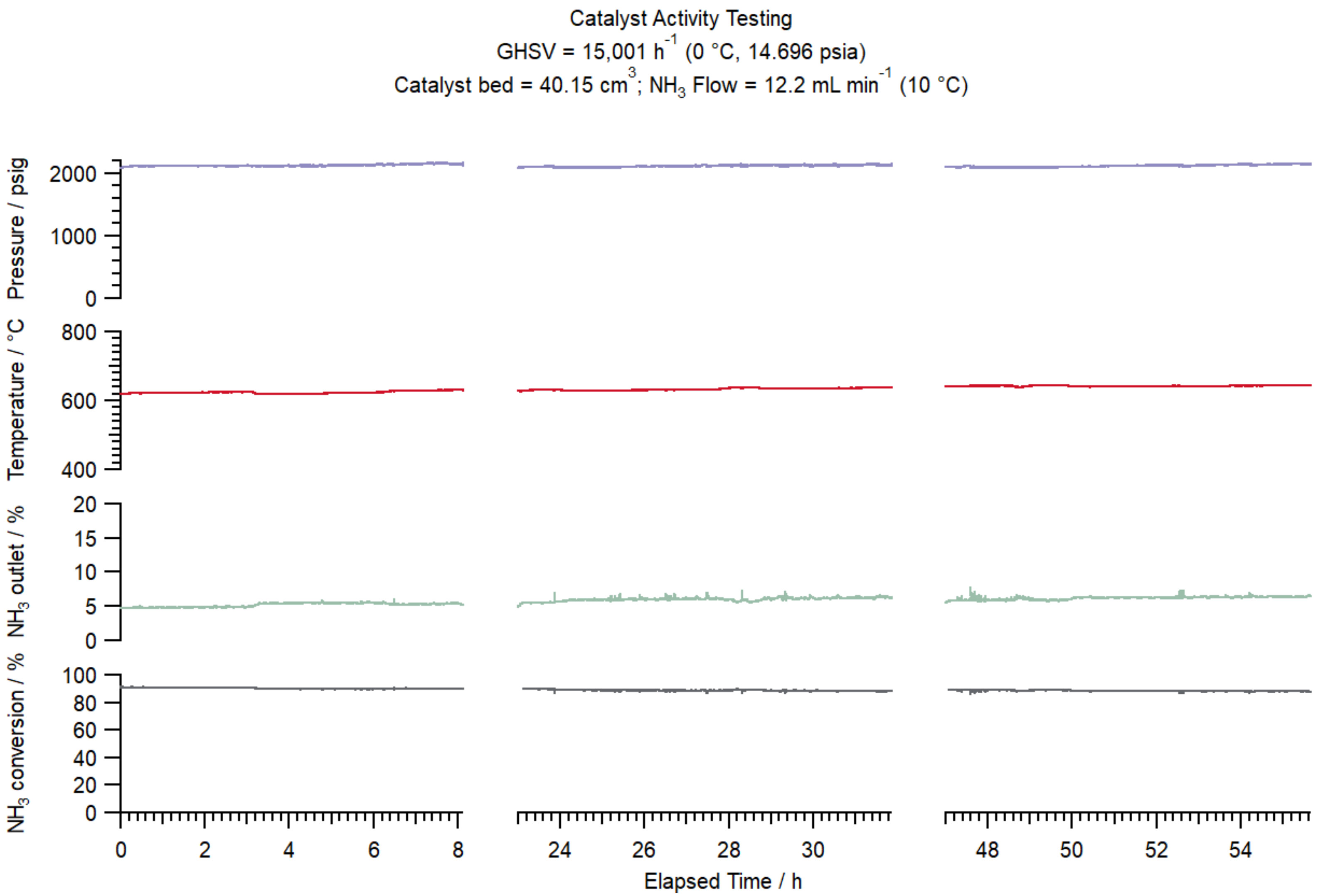
Catalyst Durability Testing: Stability at High Temp. & Press.



Catalyst Stability ≥24 hours

- Activity testing & degreening 71.4 hours prior to stability test
- Conversion ≥88 % at 633 °C for GHSV = 15,000 h^{-1} & P>2000 psia
- Durability spanned 3-days of testing
- Total durability test time = 25.5 h √
- Unattended rig operation will be enabled for 250-h durability testing

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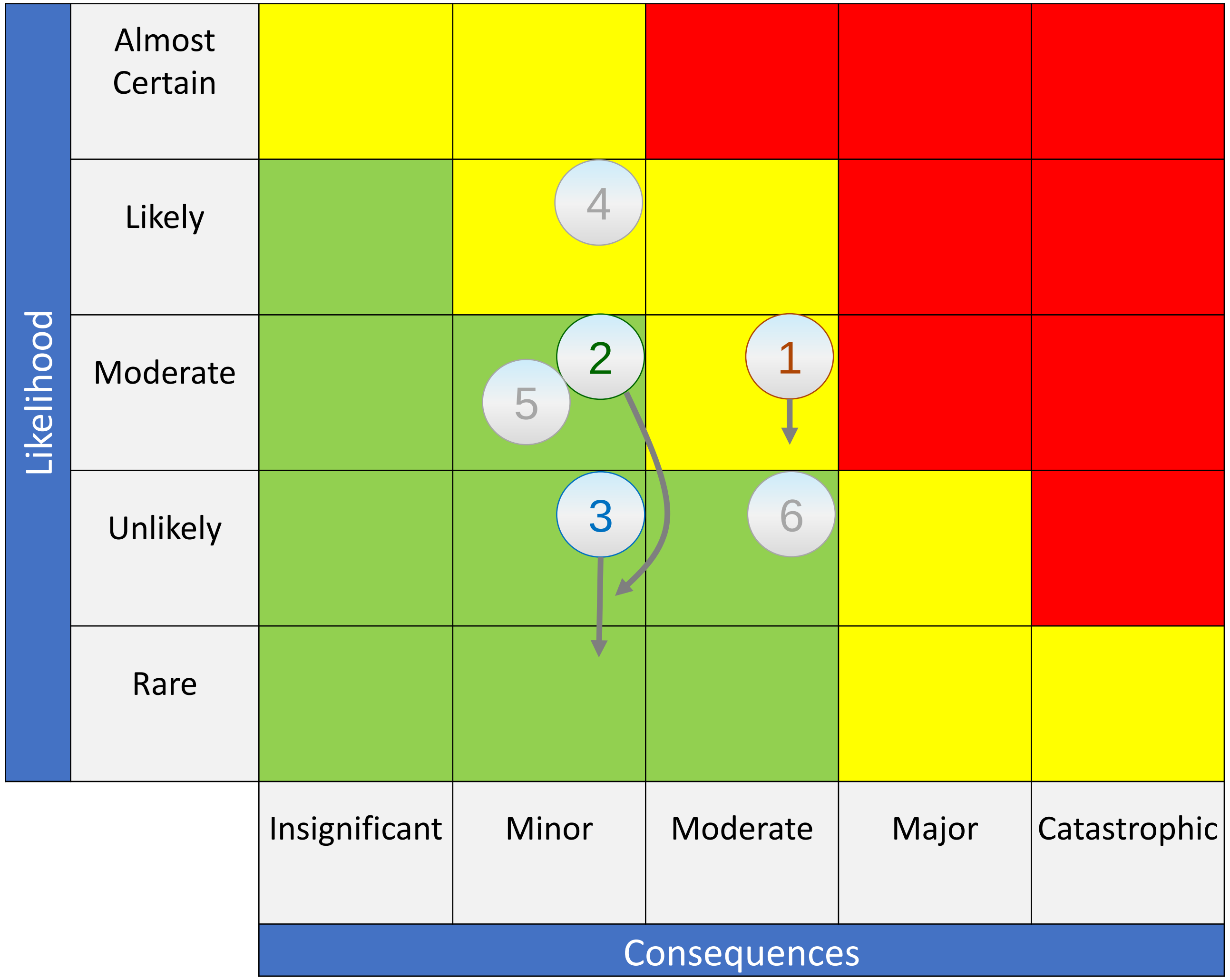
ZAPturbo - Addressing Ph-1 Risks: CRACKING, SYSTEM PERF., NH_3 FUEL SYS.



X Start of project

Risk	#
Ammonia safety, handling, and/or material compatibility concerns	1 (Ph-1) EH&S, Turbo, Infrast.-pending
Unsatisfactory NH_3 cracking catalyst performance	2 (Ph-1) Promising catalyst activity @ P
Plant integration: component mismatch across mission (lapse)	3 (Ph-1) System eval. @ Cruise & T.O.
Plant integration demo: control of transients, startup/shutdown	4 (Ph-2)
Ammonia combustion: NOx emissions due to fuel-bound N	5 (Ph-2)
Ammonia combustion: stability & anchoring – unknown @ GT cond.	6 (Ph-2)

CHANGING WHAT'S POSSIBLE

Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)

Annual Program Review Meeting
June 28th, 2022 – Cleveland, OH